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Net global warming potential and greenhouse gas intensity in a double-cropping cereal rotation as affected by nitrogen and straw management

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Abstract. The effects of nitrogen and straw management on global warming potential (GWP) and greenhouse gas intensity (GHGI) in a winter wheat–summer maize double-cropping system on the North China Plain were investigated. We measured nitrous oxide (N_2O) emissions and studied net GWP (NGWP) and GHGI by calculating the net exchange of CO_2 equivalent (CO_2-eq) from greenhouse gas emissions, agricultural inputs and management practices, as well as changes in soil organic carbon (SOC), based on a long-term field experiment established in 2006. The field experiment includes six treatments with three fertilizer N levels (zero N (control), optimum and conventional N) and straw removal (i.e. N_0, N_{opt} and N_{con}) or return (i.e. SN_0, SN_{opt} and SN_{con}). Optimum N management (N_{opt}, SN_{opt}) saved roughly half of the fertilizer N compared to conventional agricultural practice (N_{con}, SN_{con}), with no significant effect on grain yields. Annual mean N_2O emissions reached 3.90 kg N_2O-N ha^{-1} in N_{con} and SN_{con}, and N_2O emissions were reduced by 46.9 % by optimizing N management of N_{opt} and SN_{opt}. Straw return increased annual mean N_2O emissions by 27.9 %. Annual SOC sequestration was 0.40–1.44 Mg C ha^{-1} yr^{-1} in plots with N application and/or straw return. Compared to the conventional N treatments the optimum N treatments reduced NGWP by 51 %, comprising 25 % from decreasing N_2O emissions and 75 % from reducing N fertilizer application rates. Straw return treatments reduced NGWP by 30 % compared to no straw return because the GWP from increments of SOC offset the GWP from higher emissions of N_2O, N fertilizer and fuel after straw return. The GHGI trends from the different nitrogen and straw management practices were similar to the NGWP. In conclusion, optimum N and straw return significantly reduced NGWP and GHGI and concomitantly achieved relatively high grain yields in this important winter wheat–summer maize double-cropping system.

1 Introduction

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the three most important greenhouse gases (GHGs) because of their positive increases in radiative forcing and their longevity in the atmosphere (Mosier et al., 2006; IPCC, 2007). Agricultural GHG emissions were estimated to be 5.1–6.1 Pg (1 Pg $= 10^{15}$ g) CO_2 equivalents (CO_2-eq) in 2005, representing 10–12 % of total global anthropogenic emissions (Smith et al., 2007). Furthermore, agricultural GHG emissions account for roughly 20 % of the increment in radiative forcing of climate change each year (Cole et al., 1997). The mitigation potential from agriculture (excluding fossil fuel offsets from biomass) was estimated to be about 5.5–6.0 Pg CO_2-eq yr^{-1} if global agricultural techniques were improved by 2030 (Smith et al., 2008). Therefore, agricultural ecosystems are not only a very important source of GHG emissions but also present substantial opportunities for mitigation (Snyder et al., 2009).

In addition to edaphic and climatic conditions, agricultural management practices such as tillage, straw management, fertilization, irrigation and crop rotation significantly affect GHG emissions (Robertson et al., 2000; Huang et al., 2004;

Mosier et al., 2006). Many long-term field experiments have indicated that proper fertilization together with straw return can increase soil organic carbon (SOC) content (Huang and Sun, 2006; Mosier et al., 2006; Zhang et al., 2010; Shang et al., 2011). However, these practices may also stimulate N_2O emissions by increasing the supply of substrates for soil nitrifiers and denitrifiers, and the resulting increase in microbial activity may offset the SOC sequestration effects (Pathak et al., 2005). Field practices that change some soil conditions to mitigate one form of GHG emissions may bring about favourable conditions for other forms of emissions and thereby change the overall balance of GHGs (Pathak et al., 2005; Shang et al., 2011; Ma et al., 2013). To measure these overall effects in any given system the concept of net global warming potential (NGWP) was proposed based on the radiative properties of all the GHG emissions and carbon fixation, expressed as CO_2-eq ha^{-1} yr^{-1}, to give an integrated evaluation of whether the system is positive or negative in terms of CO_2-eq (Robertson and Grace, 2004). Furthermore, in order to measure the magnitude of GHG emissions to produce the same crop yield, another concept, greenhouse gas intensity (GHGI), was introduced and is expressed as the GWP of per unit of crop yield (Mosier et al., 2006). This concept can assist in solving the global challenges of increasing food production and concomitantly decreasing emissions. This also raises the important question of the potential for indirect land use change and GWP by clearing carbon-rich natural ecosystems for crop production (Tilman et al., 2002; Foley et al., 2011).

The North China Plain (NCP) covers an area of 35 million hectares and is one of the most important cereal production areas in China (Ding et al., 2011). Winter wheat–summer maize double-cropping rotations are the dominant cropping system in this region, and rational fertilization, irrigation and straw management are key factors for production of relatively high target yields, nutrient and water use efficiencies, and sustainable environmental conditions (Chen et al., 2011; Meng et al., 2012). Due to numerous interacting economic, social, and policy factors – e.g low on-farm incomes and high off-farm incomes, poor extension services, and relative low N fertilizer prices through subsidies for N fertilizer manufacturers over the last two decades – fertilizer N application rates are in general 30 to 60 % above the agronomic or recommended levels, with N application rates of 325 and 263 kg N ha^{-1} for winter wheat and summer maize, respectively, in conventional farming practice (Ju et al., 2009). The overuse of fertilizer N in the past will inevitably bring about a range of environmental consequences such as N_2O emissions (Gao et al., 2011; Ju et al., 2011), nitrate leaching (Ju et al., 2009), soil acidification (Guo et al., 2010) and air pollution (Liu et al., 2013). Recently, our results have shown that N_2O emissions can be reduced by 61.5 % by optimizing N management compared to local farming practice (Ju et al., 2011) and consequently reduce emissions of CO_2-eq during the manufacture of N fertilizers (Zhang et al., 2013). However, the SOC content of topsoils on the NCP has increased over the last two decades due to high application rates of synthetic fertilizers and straw return (Huang and Sun, 2006). It remains unclear to what extent NGWP and GHGI can be reduced following optimum N and straw management in this cropping system in comparison with conventional farming practice.

The energy used for irrigation, fuel consumption for farm operations and application of agrochemicals in crop production systems can also produce large amounts of CO_2-eq, which should be taken into account in the estimation of emission sources contributing to GWP (Mosier et al., 2006; Snyder et al., 2009). In our region the winter wheat must be irrigated (about 400 mm) to ensure relatively high grain yields because the precipitation during the dry growing season represents only 20–30 % of annual rainfall (Meng et al., 2012). Over-exploitation of the groundwater by agriculture for irrigation during the last three decades has lowered the water level (Wang et al., 2002), and the operation of the pumps requires more electricity, which is mostly generated by coal combustion, thus emitting more CO_2-eq (Zhang et al., 2013). The tillage practices developed in the last two decades for this cropping system are also unique, i.e. winter wheat straw mulching and direct seeding of summer maize without tillage, with only annual moldboard ploughing to incorporate maize straw and sow winter wheat and thus promote SOC sequestration and reduce the amount of fuel required for tillage (Huang et al., 2011) as compared to deep tillage for every crop in the past. Moreover, this cropping system normally serves as small sink for CH_4, and most results show that CH_4 uptake is almost 1 kg CH_4-C ha^{-1} yr^{-1} (Gao, 2012; Liu et al., 2012; Hu et al., 2013). The unique features of soil and climatic conditions together with the management practices of this double-cropping system make it interesting for us to know the integrated changes in GHG emissions after optimum N and straw management in comparison with conventional farming practice. To our knowledge, few studies have examined the NGWP and/or GHGI of this cropping system (Gao, 2012; Song et al., 2013), and the sources of emissions and carbon fixation were not taken fully into consideration in those studies that did, and as such the tradeoffs between the GWP sources and sinks remain to be explored.

The objectives of the present study were to investigate the effects of N application rate and straw return on grain yield, N_2O emissions, topsoil SOC sequestration and the tradeoffs among these in order to calculate and evaluate NGWP and GHGI over two cycles of the double-cropping cereal system based on a long-term field experiment with three N application rates and two straw management practices (with and without straw return).

Table 1. Treatments of the long-term field experiment.

Treatments	Nitrogen management	Straw management
N_0	No N application	wheat and maize straw removing
N_{opt}	Improved Nmin test	wheat and maize straw removing
N_{con}	Conventional farming practice	wheat and maize straw removing
SN_0	No N application	wheat straw mulching and maize straw returning
SN_{opt}	Improved N_{min} test	wheat straw mulching and maize straw returning
SN_{con}	Conventional farming practice	wheat straw mulching and maize straw returning

2 Materials and methods

2.1 Description of study site

The long-term field experiment started in October 2006 and is located at Shangzhuang Research Station (39°48′ N, 116°28′ E) of China Agricultural University in suburban Beijing. The site is at an altitude of 40 m and has a typical continental monsoon climate. Annual cumulative mean temperature for days with mean temperatures above 10 °C is 4000–5000 °C and the annual precipitation is 500–700 mm, of which 60–70 % occurs during the period from July to September. The air temperature and soil temperature at 10 cm depth, as well as precipitation and irrigation from June 2011 to June 2013, are shown in Fig. 1. The top 20 cm of the calcareous fluvo-aquic soil has a 28 % clay content, 32 % silt, 40 % sand and a pH of 8.1 (soil : water ratio 1 : 2.5). The bulk density is 1.31 g cm^{-3} and the SOC content is 7.1 g kg^{-1}, total N 0.8 g kg^{-1}, NO_3-N 24.5 mg kg^{-1}, NH_4-N 1.20 mg kg^{-1}, Olsen P 7.8 mg kg^{-1} and available K 76.2 mg kg^{-1}. Detailed information about the study site was presented in a previous paper (Qiu et al., 2012).

2.2 Experimental design

The study involved six treatments with three N levels (zero N (control), optimum and conventional N) with straw removal (i.e. N_0, N_{opt} and N_{con}) and return (i.e. SN_0, SN_{opt} and SN_{con}) (Table 1). The design was a completely randomized block with three replicates and each plot was 8 m × 8 m = 64 m^2. Winter wheat was sown at the beginning of October and harvested in the middle of the June of the following year, and summer maize was sown immediately after the wheat and harvested at the end of September. Winter wheat received basal and top-dressed N fertilizer. N rates were estimated according to the synchronization of crop N demand and soil N supply in SN_{opt} and N_{opt}, i.e. the target crop N demand minus NO_3-N in the root zone. The target crop N demands for basal application and topdressing were 100 and 200 kg N ha^{-1} in the corresponding root zone depths 0–40 and 0–100 cm, respectively (Qiu et al., 2012); in N_{con} and SN_{con}, N rates followed local conventional farming practice, i.e. 150 kg N ha^{-1} as basal fertilizer followed by ploughing and 150 kg N ha^{-1} at the shooting stage of wheat (Zhao

et al., 2006). For summer maize, N_{con} was 130 kg N ha^{-1} at the four- and ten-leaf stages; the target crop N demands for N_{opt} were 100 and 160 kg N ha^{-1} topdressing at the four- and ten-leaf stages with the corresponding root zone depths 0–60 and 0–100 cm, respectively, as recommended by Zhao et al. (2006). Phosphorus and potassium fertilizer were applied only as basal fertilizer for winter wheat at rates of 160 kg P_2O_5 ha^{-1} yr^{-1} and 90 kg K_2O ha^{-1} yr^{-1}.

2.3 Field management

The row spacing of winter wheat (var. Nongda 211) was 15 cm and the sowing rate was 225 kg ha^{-1}. The distances in summer maize (var. Zhengdan 958) between rows and plants were 60 and 25 cm, respectively. Chemical fertilizers and chopped maize straw were incorporated into the soil with tillage at the beginning of October before wheat was sown, and the topdressing N fertilizer was broadcast at the shooting stage of wheat followed by irrigation. N fertilizer was broadcast before a precipitation event or supplementary irrigation at the four- and ten-leaf stages of summer maize; the wheat straw was mulched on the soil surface after the wheat harvest. Both maize and wheat straws were mechanically chopped into 5–8 cm lengths. All the plants in straw removal plots were cut down manually and removed after yield sampling by hand.

Winter wheat was irrigated before the winter freeze in the year of sowing and at shooting, heading and grain filling. The irrigation rate was dependent on the soil moisture conditions, i.e. 60, 60, 0 and 50 mm in 2011–2012, and 60, 60, 50 and 50 mm in 2012–2013. An additional 40 mm of irrigation was supplied to the winter wheat seedlings on 3 October 2011. No irrigation was used for summer maize seedlings in 2011 and 2012 because of rain events. Pesticide (a mixture of dichlorovos and dimethoate) was sprayed on wheat in the middle of April and the middle or end of May. The same pesticide mixture and herbicide (acetochlor) were sprayed after summer sowing of maize. The liquid pesticide mixture was applied again at the beginning of July and a solid granular pesticide (carbofuran) was applied to the top leaves of summer maize at the beginning of August.
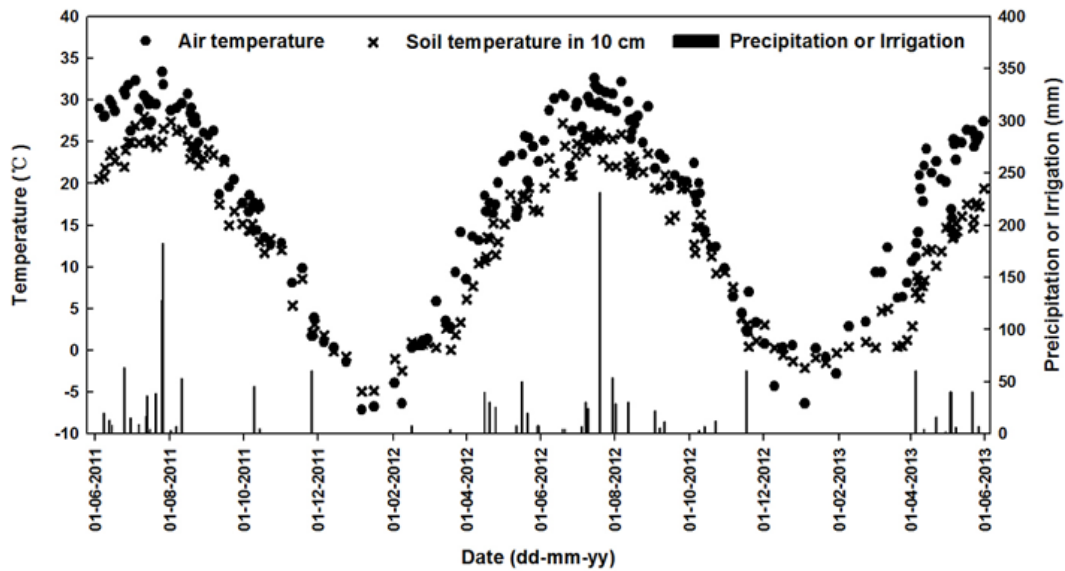
Fig. 1. Air temperature, soil temperature at 10 cm depth, and precipitation or irrigation in the winter wheat–summer maize double-cropping system from June 2011 to June 2013.

2.4 Topsoil SOC measurement

Soil samples were taken to a depth of 20 cm from each plot before summer maize harvest to determine the SOC content. Each sample was a composite of five subsamples which were taken randomly from each plot. Samples were passed through a 2 mm sieve and visible plant residues were removed after air drying. The SOC content was determined with a CN analyser (Vario Max CN, Elementar, Hanau, Germany) after soaking for 24 hours in excess of $0.3 \, \mathrm{mol} \, \mathrm{L}^{-1}$ HCl solution to remove calcium carbonate ($CaCO_3$) and oven-drying at 65 °C. We also measured the topsoil (0–20 cm) bulk density by the cutting-ring method annually after the maize harvest. Because the changes in SOC content at the depths of 20–40 and 40–60 cm were very small over the last 6 years and not significantly different between treatments, we calculated the SOC content in the different treatments only in the top 20 cm of the soil profile.

The topsoil SOC content ($\mathrm{g} \, \mathrm{kg}^{-1}$) increased annually during the period 2006–2012 in all treatments except N_0 (Fig. 2). Linear regression was therefore used to simulate the annual rate of increase of SOC content for all treatments:

$$SOC = at + b, \tag{1}$$

where t is the duration of the experiment (years since 2006). Annual topsoil organic carbon sequestration rate (SOC_{SR}, kg $C \, \mathrm{ha}^{-1} \, \mathrm{yr}^{-1}$) was estimated on the basis of the rate of increase of topsoil SOC content (d_{SOC}/d_t, g $C \, \mathrm{kg}^{-1} \, \mathrm{yr}^{-1}$). Based on Eq. (1), d_{SOC}/d_t was estimated by a. Therefore, SOC_{SR} was estimated using the following equation:

$$SOC_{SR} = a \times B \times 20 \times 100, \tag{2}$$

where B is the bulk density ($\mathrm{g} \, \mathrm{cm}^{-3}$) of the topsoil (0–20 cm). The numbers 20 and 100 in the equation are the topsoil depth and the area conversion coefficient, respectively. Similarly, the $SOC_{density}$ ($\mathrm{Mg} \, C \, \mathrm{ha}^{-1}$) was calculated by

$$SOC_{density} = c \times B \times 20/10, \tag{3}$$

where c and B are the SOC content and bulk density of the topsoil (0–20 cm), respectively. The numbers 20 and 10 in the equation are the topsoil depth and the area conversion coefficient, respectively.

2.5 Plant measurement

The above-ground biomass was measured in the middle of each plot at the winter wheat harvest within an area of $9 \, \mathrm{m}^2$ ($3 \, \mathrm{m} \times 3 \, \mathrm{m}$). Grain and straw samples were oven-dried at 65 °C until constant weight to determine dry matter yield. In the case of summer maize $14.4 \, \mathrm{m}^2$ (six rows 4 m in length) in the middle of each plot were harvested to determine the fresh ear and stover yields together with ear number. Five plants were randomly sampled from the harvested summer maize and separated into grains, cobs and stover to determine the oven-dried weight at 65 °C. The grain yield of maize was estimated by deduction of cob yield. The C content in straw was determined using a CN analyser (Vario Max CN, Elementar, Hanau, Germany).

2.6 N_2O emission measurements

N_2O emissions were measured manually in two cycles of winter wheat–summer maize from 2011 to 2013 using the closed static chamber method (Mosier et al., 2006). Before the wheat was sown, two types of base collar

(length × width = 60 cm × 50 cm and 60 cm × 30 cm) made of stainless steel were inserted 20 cm into the soil in every plot. These collars were removed only once per year before tillage after summer maize harvest and remained in position during the whole crop rotation. Type I chambers (length × width × height = 60 cm × 50 cm × 50 cm) were designed to measure N_2O emissions from the winter wheat season and early stages of summer maize (before 50 cm height). The two parts of type I chambers were sealed by a groove filled with water on the top edge of the base collar. If the maize height surpassed 50 cm, type II chambers (length × width × height = 60 cm × 30 cm × 20 cm) were used, separated vertically into two parts and with a hole (11 cm diameter) drilled in the centre of the top of the chamber (Liu et al., 2012). Type II chambers allowed the cornstalks to pass through the chamber tops, and as a result only the maize roots were covered. The gaps between the type II chambers and cornstalks were sealed using a preservative film (1.2 μm-thick polyvinylidene chloride) when the chambers were closed. The two parts of type II chambers were sealed with rubber. Each chamber was covered with a layer of insulating material to minimize any chamber effects on air temperature to < 3 °C in the headspace during gas sampling, and the interior of the chamber was equipped with two opposing ventilators to ensure complete mixing of air. The first sample was collected immediately from the chamber roof after the chamber was enclosed. Four gas samples were collected at intervals of 15 min using 50 mL plastic injectors through a three-way stopcock and a Teflon tube connected to the chamber. Daily measurements were carried out for about 10 days and 5 days after fertilizer application and rainfall or irrigation, respectively, for the remaining periods emissions were measured twice per week and once a week when the soil was frozen (Hu et al., 2013). The sampling time was between 08:00 and 11:00 a.m. of the local time.

Gas samples were analysed for N_2O using a modified gas chromatograph (GC; Agilent 6820, USA) equipped with a ^{63}Ni-electron capture detector (ECD) running at 350 °C. High-purity dinitrogen (N_2, 99.999 %) was used as the carrier gas for N_2O analysis and 10 % CO_2 in pure N_2 as a make-up gas for ECD (Zheng et al., 2008). The detection limits of the GC were 2 μg N m^{-2} h^{-1} for N_2O at a chamber height of 50 cm. The GC was calibrated using known concentrations of mixed gas (0.354 ppm N_2O in pure N_2) which was calibrated using standard calibration gases during each group measurement cycle, and air conditioning was used for temperature stabilization during measurement in the laboratory to minimize the tendency of the ECD to drift with changing temperature.

Taking into account the methodology for calculating the fluxes of N_2O emissions from some previous studies, the N_2O fluxes were calculated by linear regression (Eq. 5) or nonlinear (Eq. 6) methods according to the changing pattern of gas concentration in the headspace of the closed chamber

(Livingston et al., 2005; Kroon et al., 2008). The flux of N_2O emission (μg N_2O-N ha^{-1} d^{-1}) was calculated as

$$F = k_1 \times P_0/P \times 273/(273 + T) \times 28/22.4 \times 0.5 \times dc/dt \qquad (4)$$

$$c = a + bt \, (dc/dt = b), \qquad (5)$$

$$c = a + bt + dt^2 \, (dc/dt = b), \qquad (6)$$

where F (μg N_2O-N m^{-2} h^{-1}) is the flux; k_1 is a coefficient (0.001) for dimensional conversion; P_0 is air pressure incubation (hPa); P is the ambient air pressure at the experimental site (1013 hPa); $P_0/P \approx 1$ because the altitude of the experimental site is 40 m and very close to sea level; T (°C) is mean air temperature in the chamber; 28 (g N_2O-N mol^{-1}) is the molecular weight of N_2 in the N_2O molecule; 22.4 (L mol^{-1}) is the molecular volume at 1, 013 hPa and 273 K; 0.5 (m) is the chamber height; c (ppm) is the concentration of N_2O; t (h) is the time of chamber closure; and dc/dt (μL L^{-1} h^{-1}) is the rate of increase in N_2O concentration in the chamber (Zheng et al., 2008). $P_0/P \times 273/(273 + T)$ is the temperature- and pressure-corrected mole volume. dc/dt is the slope of the curve which was calculated depending on the pattern of the concentration changes in the headspace (Kroon et al., 2008), and a, b and d are constants. N_2O emissions are the mean values of three replicates on the sampling days. The seasonal or annual cumulative N_2O emissions were estimated from the sum of measurement and no-measurement days, which was estimated by linear interpolation (Mosier et al., 2006).

2.7 NGWP and GHGI calculation

To better understand climatic effects of the nitrogen and straw management on winter wheat–summer maize double-cropping system, the NGWP and GHGI were calculated using the following equations.

$$N_2O_{GWP} = N_2O \left(kgN_2O-N ha^{-1} \right)/28 \times 44 \times 298, \qquad (7)$$

where 28 is the molecular weight of N in N_2O and 44 is the molecular weight of N_2O. The global warming potentials of 1 kg N_2O is equivalent to 298 kg CO_2 based on 100 years (IPCC, 2007).

$$CH_{4 \, GWP} = CH_4 \left(kgCH_4-C ha^{-1} \right)/12 \times 16 \times 25, \qquad (8)$$

where 12 is the molecular weight of C in CH_4 and 16 is the molecular weight of CH_4. The global warming potential of 1 kg CH_4 is equivalent to 25 kg CO_2 based on 100 years (IPCC, 2007). We adopted CH_4 uptake by 1 kg CH_4-C ha^{-1} yr^{-1}, the result from two continuous years of study
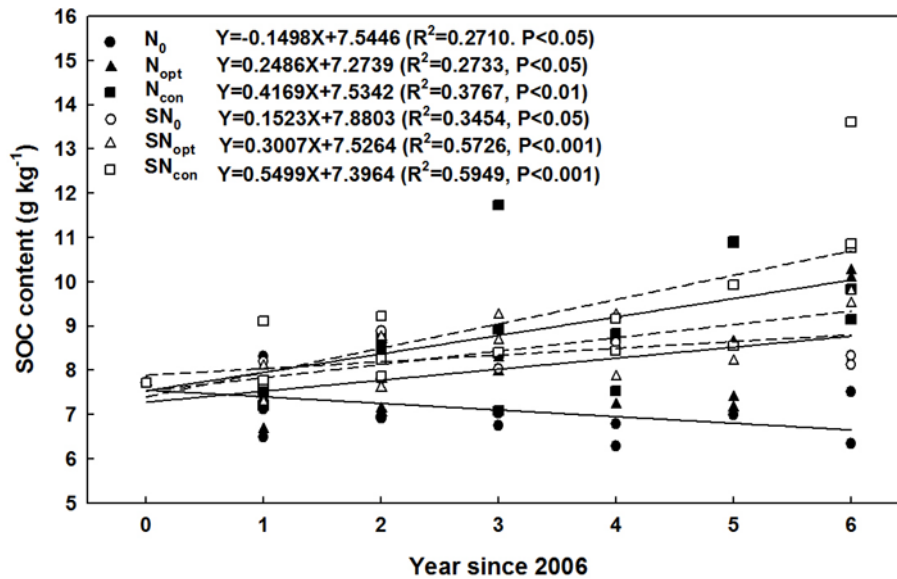
Fig. 2. Changes in soil organic carbon (SOC) in the top 20 cm of the soil profile in the winter wheat–summer maize double-cropping system from 2006 to 2012. The dashed line and solid line were fitted by linear regression from straw and without straw treatments, respectively.

using the same cropping system and climatic zone (Hu et al., 2013).

$$SOC_{GWP} = SOC_{SR} \left(kg\,C\,ha^{-1} \right) / 12 \times 44, \tag{9}$$

where the 12 is the molecular weight of C in CO_2 and 44 is the molecular weight of CO_2.

$$Fertilizer_{GWP} = N\,rate \left(kg\,N\,ha^{-1} \right) \times 8.3 + P_2O_5\,rate$$
$$\left(kg\,P_2O_5\,ha^{-1} \right) \times 1.51 + K_2O\,rate \tag{10}$$
$$\left(kg\,K_2O\,ha^{-1} \right) \times 0.98,$$

where the 8.3, 1.51 and 0.98 are the GHG emissions (kg CO_2-eq kg^{-1}) associated with the manufacture and transportation of fertilizer N (Zhang et al., 2013), P and K (Huang et al., 2011), respectively. The date, type and rate of fertilizer applications were recorded in detail.

$$Power_{GWP} = Electricity\,(kW) \times time(h) \times 1.30, \tag{11}$$

where 1.30 (kg CO_2-eq (kW h)$^{-1}$) is the GHG emission (kg CO_2-eq kg^{-1}) associated with the production and utilization of electricity by coal combustion (Zhang et al., 2013). The duration of every irrigation event and the pump power consumption were recorded in detail. The electricity consumption for irrigation was sum of the duration of all irrigation events multiplied by the power of the pump.

$$Fuel_{GWP} = Diesel\,oil(L) \times 3.94, \tag{12}$$

where 3.94 (kg CO_2-eq L^{-1}) is the GHG emission (kg CO_2-eq kg^{-1}) associated with diesel oil combustion (Huang et al., 2011). The energy consumption of every farm machinery operation was recorded in detail. The annual consumption of diesel oil by farm machinery operations was 64 and

70 L ha^{-1} from the straw removal and return treatments, respectively.

$$Pesticide_{GWP} = Pesticide(kg) \times 18.0, \tag{13}$$

where 18.0 (kg CO_2-eq kg^{-1}) is the GHG emission (kg CO_2-eq kg^{-1}) associated with pesticide production (Huang et al., 2011). The dates, types and rates of pesticide application were recorded in detail. The annual consumption of pesticide was 6.2 kg ha^{-1}.

$$Net\text{-}GWP = N_2O_{GWP} - SOC_{GWP} - CH_{4\,GWP}$$
$$+ Fertilizer_{GWP} + Power_{GWP} + Fuel_{GWP} \tag{14}$$

$$GHGI = Net\text{-}GWP/grain\,yield \tag{15}$$

The units of NGWP and GHGI are kg CO_2-eq ha^{-1} yr^{-1} and kg CO_2-eq Mg^{-1} yr^{-1} grain, respectively.

2.8 Statistical analysis

The primary data were examined using Microsoft Excel spreadsheets. The grain yield, seasonal and annual N_2O emissions and SOC density of the different treatments were tested by analysis of variance and mean values were compared by least significant difference (LSD) at the 5 % level using the SAS statistical software package (version 8.2; SAS Institute, Inc., Cary, NC).

Table 2. Fertilizer N rates (kg N ha^{-1}) in the winter wheat–summer maize cropping system from October 2006 to September 2012.

Treatments[a]	2006–2007		2007–2008		2008–2009		2009–2010		2010–2011		2011–2012		Mean of six years	
	WW[b]	SM	WW	SM	WW	SM	WW	SM	WW	SM	WW	SM	WW	SM
N_0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{opt}	86	45	139	132	127	130	150	30	110	212	150	130	127	113
N_{con}	300	260	300	260	300	260	300	260	300	260	300	260	300	260
SN_0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SN_{opt}	126	93	181	151	114	132	150	30	107	159	150	130	138	116
SN_{con}	300	260	300	260	300	260	300	260	300	260	300	260	300	260

[a] N_0, N_{opt} and N_{con} represent zero-N (control), optimum and conventional N, respectively. S represents straw return. [b] WW and SM are winter wheat and summer maize; number is mean ± standard error ($n = 3$); N application in 2006–2009 was retrieved from Qiu et al. (2012).

Table 3. Grain yield (dry matter, Mg ha^{-1}) in winter wheat–summer maize double-cropping system from October 2010 to October 2012.

Treatments[a]		2010–2011	2011	2010–2011	2011–2012	2012	2011–2012	2010–2012
Nitrogen	Straw	WW[b]	SM	Annual yield	WW	SM	Annual yield	Mean annual yield
Treatment effect ($n = 3$)								
N_0		$2.67 \pm 0.38b$[c]	$5.43 \pm 0.40b$	$8.10 \pm 0.63c$	$2.39 \pm 0.31b$	$3.94 \pm 0.35c$	$6.33 \pm 0.63b$	$7.21 \pm 0.14b$
N_0	S	$2.86 \pm 0.44b$	$4.99 \pm 0.33b$	$7.86 \pm 0.70c$	$2.50 \pm 0.36b$	$4.48 \pm 0.59c$	$6.98 \pm 0.95b$	$7.42 \pm 0.74b$
N_{opt}		$5.40 \pm 0.59a$	6.52 ± 0.84ab	11.92 ± 1.11ab	$4.27 \pm 0.61a$	$6.08 \pm 0.31b$	$10.35 \pm 0.91a$	$11.14 \pm 0.92a$
N_{opt}	S	$5.35 \pm 0.23a$	$5.94 \pm 0.73b$	$11.29 \pm 0.87b$	$4.70 \pm 0.37a$	6.46 ± 0.36ab	$11.16 \pm 0.60a$	$11.23 \pm 0.60a$
N_{con}		$5.51 \pm 0.11a$	6.49 ± 1.11ab	12.00 ± 1.14ab	$4.53 \pm 0.42a$	$7.29 \pm 0.36a$	$11.82 \pm 0.78a$	$11.91 \pm 0.73a$
N_{con}	S	$5.65 \pm 0.80a$	$7.85 \pm 0.27a$	$13.50 \pm 0.89a$	$4.58 \pm 0.41a$	$7.30 \pm 0.26a$	$11.88 \pm 0.67a$	$12.69 \pm 0.75a$
Nitrogen effect ($n = 6$)								
N_0mean		$2.77 \pm 0.27b$	$5.21 \pm 0.17b$	$7.98 \pm 0.35b$	$2.44 \pm 0.32b$	$4.21 \pm 0.47c$	$6.65 \pm 0.78c$	$7.32 \pm 0.40c$
N_{opt}mean		$5.38 \pm 0.27a$	6.23 ± 0.53ab	$11.61 \pm 0.56a$	$4.49 \pm 0.16a$	$6.27 \pm 0.21b$	$10.76 \pm 0.37b$	$11.18 \pm 0.19b$
N_{con}mean		$5.58 \pm 0.35a$	$7.17 \pm 0.43a$	$12.75 \pm 0.66a$	$4.55 \pm 0.41a$	$7.30 \pm 0.31a$	$11.85 \pm 0.72a$	$12.30 \pm 0.66a$
Straw effect ($n = 9$)								
Without straw		$4.53 \pm 0.12a$	$6.15 \pm 0.23a$	$10.67 \pm 0.12a$	$3.73 \pm 0.41a$	$5.77 \pm 0.32a$	$9.50 \pm 0.73a$	$10.09 \pm 0.31a$
With straw		$4.62 \pm 0.32a$	$6.26 \pm 0.26a$	$10.88 \pm 0.26a$	$3.93 \pm 0.16a$	$6.08 \pm 0.31a$	$10.01 \pm 0.46a$	$10.44 \pm 0.25a$

[a] N_0, N_{opt} and N_{con} represent zero-N (control), optimum and conventional N, respectively. S is straw returning. [b] WW and SM are winter wheat and summer maize; number is mean±standard error ($n = 3$). [c] Different letters within same column denote significant differences ($P < 0.05$).

3 Results

3.1 N Fertilizer rate and grain yield

The optimum N management (N_{opt} and SN_{opt}) with the improved Nmin test significantly reduced N fertilizer rate to both crops compared to conventional farming practice (N_{con} & SN_{con}), which saved 54–58, 56–57 and 55–57 % N fertilizer in winter wheat, summer maize and annually, respectively (Table 2). Application of N (N_{opt} and N_{con}) significantly increased the grain yield by 20–94 and 38–101 %, respectively, compared to the control, but there was no significant difference between N_{opt} and N_{con} except in maize in 2012 (Table 3). Although there was almost 3.7–5.5 Mg C ha^{-1} yr^{-1} straw input in treatments SN_0, SN_{opt} and SN_{con}, the yields increased by only 1.8–5.4 % over the two years (four crops) compared to the straw removal treatments.

3.2 Changes in topsoil SOC content and density

The significantly changes in SOC densities in all treatments were only found in 0–20 cm, but not in 20–40 and 40–60 cm in 2012 (Table 4). Compared to the N_0 treatment, long-term N application and straw return gradually increased topsoil SOC content by 2.9–51.9 % (Fig. 2). The topsoil SOC content rate of increase was in the sequence SN_{con} (0.55 g kg^{-1} yr^{-1}) > N_{con} (0.42 g kg^{-1} yr^{-1}) > SN_{opt} (0.30 g kg^{-1} yr^{-1}) > N_{opt} (0.25 g kg^{-1} yr^{-1}) > SN_0 (0.15 g kg^{-1} yr^{-1}), but with N_0 decreasing by 0.15 g kg^{-1} yr^{-1}.

In 2012 the topsoil SOC density of SN_{con} was the highest and was significantly higher than the other treatments (Table 4), and those of SN_{con}, N_{con}, SN_{opt} and N_{opt} were significantly higher than the N_0 treatment. As for the nitrogen application effect, N_{con} was the highest and was 4.5–13.9 % and 2.0–23.3 % higher than N_{opt} and N_0, respectively. The differences among the three N levels were not significant until 2012, when N_{con} and N_{opt} were significantly higher than N_0 ($P < 0.05$). As for the straw return effect, the 0–20 cm SOC density from straw return was 20.1–26.1 Mg C ha^{-1} across 6 years, which was 3.9–16.5 % higher than without straw, but there were no significantly differences between straw return and straw removal over the 6 yr period.
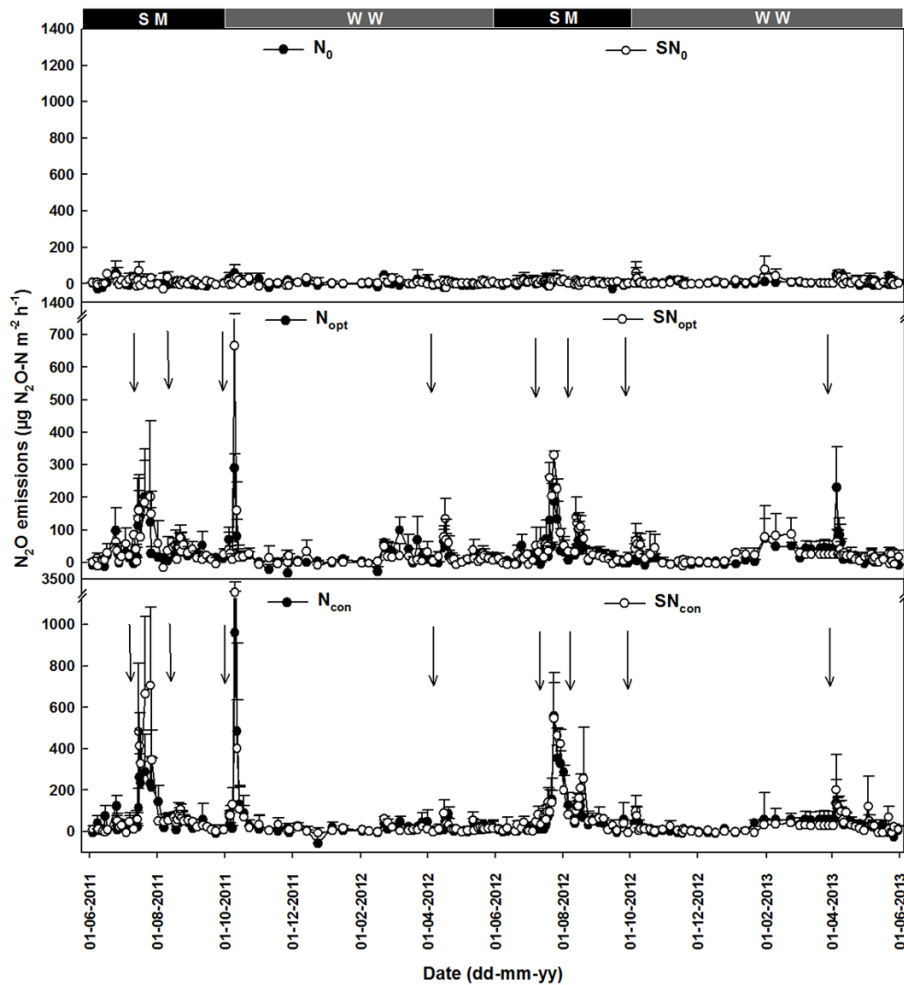
Fig. 3. Nitrous oxide (N_2O) fluxes in the winter wheat–summer maize double-cropping system from June 2011 to June 2013. The arrows show the dates of fertilizer N application.

3.3 N_2O emissions

The patterns of N_2O fluxes from June 2011 to June 2013 are shown in Fig. 3 for all treatments. The fluxes of the all plots varied from -28.3 to $1682.1\,\mu g\ N_2O\text{-N}\,m^{-2}\,h^{-1}$. Several N_2O emission peaks were observed in the fertilized treatments, which were associated with N fertilizer application events coupled with irrigation/rainfall or tillage or triggered by heavy rainfall alone, and two may have been related to the freeze–thaw effect on 20 March 2012 and 15 March 2013, when the soil temperature increased above $0\,°C$. Fertilization alone only slightly stimulated N_2O emissions within two weeks, i.e. the maximum N_2O emissions amounting to 106.9, 254.8 and $82.2\,\mu g\ N_2O\text{-N}\,m^{-2}\,h^{-1}$ after fertilization at the ten-leaf stage of 2011 maize, 2012 maize and basal fertilization in 2012–2013 wheat, respectively. When fertilization was coupled with rainfall or irrigation, massive pulses of N_2O emissions were observed, with maximum fluxes up to $230.2\,\mu g\ N_2O\text{-N}\,m^{-2}\,h^{-1}$ at shooting stage in 2012–2013

wheat, and 704.7, $556.1\,\mu g\ N_2O\text{-N}\,m^{-2}\,h^{-1}$ after four-leaf stage fertilization in 2011 and 2012 maize. The highest N_2O emission was $1682.1\,\mu g\ N_2O\text{-N}\,m^{-2}\,h^{-1}$ after the wheat was sown in October 2011 because fertilization and tillage were coupled with irrigation.

Annual cumulative N_2O emissions over the two cropping rotations ranged from 0.20 to 4.54 and 0.47 to 4.35 kg N_2O-N ha^{-1} in 2011–2012 and 2012–2013, respectively (Table 5). The seasonal cumulative N_2O emission from all treatments was in the order $SN_{con} > N_{con} > SN_{opt} > N_{opt} > SN_0 > N_0$ in these four different seasons. As for the nitrogen application effect, annual cumulative N_2O emissions in N_{opt} and N_{con} were significantly higher than N_0 ($P < 0.05$), with increases of more than 3 and 6 times, respectively. The cumulative N_2O emissions of N_{con} in 2011–2012 and 2012–2013 winter wheat were not significantly higher than N_{opt}, but the opposite trend occurred in 2011 and 2012 summer maize. As for the straw return effect, the seasonal cumulative N_2O emissions from the straw return treatments increased by 36, 28,

Table 4. Soil organic carbon (SOC) density (Mg C ha^{-1}) in 0–20, 20–40, 40–60 cm in winter wheat–summer maize double-cropping system for the year 2006 and 2012.

Treatment[a]		0–20 cm		20–40 cm		40–60 cm	
Nitrogen	Straw	2006	2012	2006	2012	2006	2012
Treatment effect ($n = 3$)							
N_0		20.2	$18.1 \pm 1.2c$[b]	19.6	$17.2 \pm 0.9a$	16.6	$15.1 \pm 0.8a$
N_0	S	20.2	$22.2 \pm 1.3bc$	19.6	$17.8 \pm 2.7a$	16.6	$16.5 \pm 0.7a$
N_{opt}		20.2	$24.2 \pm 0.5b$	19.6	$16.5 \pm 0.5a$	16.6	$16.0 \pm 1.0a$
N_{opt}	S	20.2	$25.3 \pm 2.9b$	19.6	$19.4 \pm 3.0a$	16.6	$16.3 \pm 1.4a$
N_{con}		20.2	$24.9 \pm 3.8b$	19.6	$19.9 \pm 2.6a$	16.6	$16.2 \pm 0.3a$
N_{con}	S	20.2	$30.8 \pm 4.3a$	19.6	$20.7 \pm 3.4a$	16.6	$16.7 \pm 2.2a$
Nitrogen effect ($n = 6$)							
N_0 mean		20.2	$20.2 \pm 2.1b$	19.6	$17.5 \pm 1.7a$	16.6	$15.8 \pm 0.5a$
N_{opt} mean		20.2	$24.7 \pm 4.0a$	19.6	$18.0 \pm 1.4a$	16.6	$16.2 \pm 0.4a$
N_{con} mean		20.2	$27.8 \pm 3.4a$	19.6	$20.3 \pm 2.6a$	16.6	$16.4 \pm 1.2a$
Straw effect ($n = 9$)							
Without straw		20.2	$22.4 \pm 1.3a$	19.6	$17.9 \pm 1.1a$	16.6	$15.7 \pm 0.4a$
With straw		20.2	$26.1 \pm 1.7a$	19.6	$19.3 \pm 2.3a$	16.6	$16.5 \pm 1.2a$

[a] N_0, N_{opt} and N_{con} represent zero-N (control), optimum and conventional N, respectively. S is straw return. [b] Different lowercase letters within same column denote significant differences between treatments ($P < 0.05$).

34 and 37 % compared to straw removal treatments in the four crops, respectively, but only in 2012 maize was the increase significant ($P < 0.05$). The cumulative N$_2$O emissions showed pronounced seasonal variation.

Correlations between seasonal cumulative N$_2$O emissions and fertilizer N application rates from straw removal and straw return were also calculated and the seasonal cumulative N$_2$O emissions increased linearly with increasing N application rate (Fig. 4). Compared to the straw removal treatments, the slopes from the straw return treatments were 56, 8, 23 and 10 % higher in 2011 maize, 2011–2012 wheat, 2012 maize and 2012–2013 wheat, respectively.

3.4 NGWP and GHGI

Although N fertilizer and straw return increased annual N$_2$O emissions, they also increased SOC sequestration and it is interesting to explore the NGWP and GHGI in this double-cropping system. From the view of carbon footprint, we included GHG emissions associated with all the inputs (fertilization, power, fuel, pesticide) and SOC sequestration expressed as kg CO$_2$-eq ha^{-1} yr^{-1} (Table 6). The NGWP was in the order $N_{con} > N_0 > SN_{con} > N_{opt} > SN_{opt} > SN_0$.

The NGWP of the zero-N application treatments (N$_0$ and SN$_0$) averaged 2702 kg CO$_2$-eq ha^{-1}, with a positive GWP of 2748 kg CO$_2$-eq ha^{-1} (including a 9 % contribution from N$_2$O emissions, 12 % from fertilizer production (0 % from N), 66 % from power, 13 % from fuel and pesticide) and a negative GWP of only 46 kg CO$_2$-eq ha^{-1} (including 72 and 28 % from CH$_4$ uptake and SOC sequestration, respectively). In contrast, the NGWP of optimum (N$_{opt}$ and SN$_{opt}$)

applications averaged 2853 kg CO$_2$-eq ha^{-1}, with a positive GWP of 5525 kg CO$_2$-eq ha^{-1} (including an 18 % contribution from N$_2$O emissions, 43 % from fertilizer production (37 % from N), 33 % from power, 6 % from fuel and pesticide) and a negative GWP of 2672 kg CO$_2$-eq ha^{-1} (including 99 % from SOC sequestration). The NGWP of the conventional N (N$_{con}$ and SN$_{con}$) applications averaged 4309 kg CO$_2$-eq ha^{-1}, with a positive GWP of 8986 kg CO$_2$-eq ha^{-1} (including a 20 % contribution from N$_2$O emissions, 54 % from fertilizer production (51 % from N), 20 % from power and 6 % from fuel and pesticide), and a negative GWP of 4677 kg CO$_2$-eq ha^{-1} (including 99 % from SOC sequestration). The optimum N application reduced CO$_2$-eq ha^{-1} by 3462 kg by reducing N$_2$O emissions (25 %) and N fertilizer (75 %) compared to the conventional N application, but the latter fixed over 2006 kg CO$_2$-eq ha^{-1} more than the optimum N application through increasing SOC. Thus, the optimum N application led to a reduction of only 1456 kg CO$_2$-eq ha^{-1} compared to the conventional N application, which accounted for 34 % of NGWP in the latter.

Comparing the two straw management practices, the net GWP of the straw removal treatments (N$_0$, N$_{opt}$ and N$_{con}$) averaged 3873 kg CO$_2$-eq ha^{-1}, with a positive GWP of 5558 kg CO$_2$-eq ha^{-1} (including a 15 % contribution from N$_2$O emissions, 46 % from chemical fertilizer production and transport (40 % from N), 32 % from power and 7 % from fuel and pesticide) and a negative GWP of 1685 kg CO$_2$-eq ha^{-1} (including 98 % from SOC sequestration). In comparison, the NGWP of the straw return treatments (SN$_0$, SN$_{opt}$ & SN$_{con}$) averaged 2703 kg CO$_2$-eq ha^{-1} with a positive GWP of 5948 kg CO$_2$-eq ha^{-1} (including a 20 % contribution from

Table 5. N_2O emissions (kg N_2O-N ha^{-1}) in winter wheat–summer maize double-cropping system from June 2011 to June 2013.

Treatments[a]		2011	2011–2012	2011–2012	2012	2012–2013	2012–2013	2011–2013
Nitrogen	Straw	SM[b]	WW	Annual	SM	WW	Annual	Mean annual
Treatment effect ($n = 3$)								
N_0		$0.09 \pm 0.02c$	$0.11 \pm 0.02c$	$0.20 \pm 0.04c$	$0.17 \pm 0.04e$	$0.30 \pm 0.05c$	$0.47 \pm 0.09c$	$0.34 \pm 0.03d$
N_0	S	$0.20 \pm 0.15c$	$0.34 \pm 0.11bc$	$0.54 \pm 0.16c$	$0.19 \pm 0.07e$	$0.64 \pm 0.17bc$	$0.83 \pm 0.21bc$	$0.69 \pm 0.17d$
N_{opt}		$1.09 \pm 0.33bc$	$0.89 \pm 0.29abc$	$1.99 \pm 0.25bc$	$0.72 \pm 0.06d$	$0.75 \pm 0.46bc$	$1.48 \pm 0.45b$	$1.73 \pm 0.34c$
N_{opt}	S	$1.18 \pm 0.62bc$	$0.98 \pm 0.19abc$	$2.16 \pm 0.49bc$	$1.21 \pm 0.04c$	$1.43 \pm 0.65ab$	$2.65 \pm 0.63a$	$2.40 \pm 0.26bc$
N_{con}		$1.80 \pm 0.65ab$	$1.47 \pm 0.85ab$	$3.27 \pm 0.83ab$	$1.97 \pm 0.20b$	$1.50 \pm 0.56ab$	$3.47 \pm 0.40a$	$3.37 \pm 0.32ab$
N_{con}	S	$2.71 \pm 1.05a$	$1.83 \pm 1.00a$	$4.54 \pm 1.85a$	$2.39 \pm 0.41a$	$1.96 \pm 0.63a$	$4.35 \pm 0.64a$	$4.45 \pm 1.31a$
Nitrogen effect ($n = 6$)								
N_0mean		$0.15 \pm 0.08c$	$0.23 \pm 0.05b$	$0.37 \pm 0.09c$	$0.18 \pm 0.05c$	$0.47 \pm 0.09b$	$0.65 \pm 0.12c$	$0.51 \pm 0.08c$
N_{opt}mean		$1.14 \pm 0.47b$	$0.94 \pm 0.23ab$	$2.07 \pm 0.36b$	$0.97 \pm 0.05b$	$1.09 \pm 0.47ab$	$2.06 \pm 0.45b$	$2.07 \pm 0.29b$
N_{con}mean		$2.26 \pm 0.81a$	$1.65 \pm 0.40a$	$3.90 \pm 1.20a$	$2.18 \pm 0.18a$	$1.73 \pm 0.68a$	$3.91 \pm 0.66a$	$3.90 \pm 0.69a$
Straw effect ($n = 9$)								
Without straw		$1.00 \pm 0.28a$	$0.82 \pm 0.20a$	$1.82 \pm 0.34a$	$0.95 \pm 0.07b$	$0.85 \pm 0.34a$	$1.81 \pm 0.27b$	$1.81 \pm 0.19b$
With straw		$1.36 \pm 0.60a$	$1.05 \pm 0.40a$	$2.41 \pm 0.82a$	$1.27 \pm 0.16a$	$1.34 \pm 0.27a$	$2.61 \pm 0.46a$	$2.51 \pm 0.48a$

[a] N_0, N_{opt} and N_{con} represent zero-N (control), optimum and conventional N, respectively. S is straw return. [b] WW and SM are winter wheat and summer maize; number represents mean $\pm$ standard error ($n = 3$); different letters within same column indicate significant differences ($P < 0.05$).

Table 6. Net global warming potential (NGWP) and greenhouse gas intensity (GHGI) in winter wheat–summer maize double-cropping system from June 2011 to June 2013.

Treatments*		N_2O	CH_4	SOC	Fertilizer			Power	Fuel	Pesticide	Net GWP	Grain yield	GHGI
					N	P_2O_5	K_2O						
Nitrogen	Straw				kg CO_2-eq ha^{-1}							Mg ha^{-1}	kg CO_2-eq Mg^{-1}
N_0		159	−33	−1437	0	242	88	1801	252	112	4058	7.2	562
N_0	S	323	−33	1463	0	242	88	1801	276	112	1346	7.4	181
N_{opt}		810	−33	2387	1992	242	88	1801	252	112	2877	11.1	258
N_{opt}	S	1124	−33	2889	2108	242	88	1801	276	112	2829	11.2	252
N_{con}		1578	−33	4004	4648	242	88	1801	252	112	4684	11.9	393
N_{con}	S	2084	−33	5284	4648	242	88	1801	276	112	3934	12.7	310
Nitrogen management													
N_0		241	−33	13	0	242	88	1801	264	112	2702	7.3	369
N_{opt}		967	−33	2638	2050	242	88	1801	264	112	2853	11.2	255
N_{con}		1831	−33	4644	4648	242	88	1801	264	112	4309	12.3	350
Straw management													
Without straw		849	−33	1651	2213	242	88	1801	252	112	3873	10.1	384
With straw		1177	−33	3212	2252	242	88	1801	276	112	2703	10.4	259

* N_0, N_{opt} represent zero-N (control), optimum and conventional N, respectively. S represents straw return.

N_2O emissions, 43 % from chemical fertilizer production and transport (38 % from N), 30 % from power and 7 % from fuel and pesticide) and a negative GWP of 3245 kg CO_2-eq ha^{-1} (including 99 % from SOC sequestration). Compared to the straw removal treatments, the positive GWP in the straw return treatments increased by 391 kg CO_2-eq ha^{-1}, 84 % of which is from the increment of N_2O emissions, 10 % from higher N input and 7 % from straw return, but the negative GWP also increased by 1561 kg CO_2-eq ha^{-1} because of more SOC sequestration after straw return, so the NGWP in the straw return treatments decreased by 1170 kg CO_2-eq ha^{-1} compared to straw removal, accounting for 30 % of NGWP in the latter.

The GHGI across all treatments ranged from 181 to 562 kg CO_2-eq Mg^{-1} grain and followed the order $N_0 > N_{con} > SN_{con} > N_{opt} > SN_{opt} > SN_0$ (Table 6). Comparing the three N levels, the GHGI of zero-N applications (N_0 and SN_0) averaged 369 kg CO_2-eq Mg^{-1} grain, including contributions of 34, 45, 246, 51, −5 and −2 CO_2-eq Mg^{-1} from N_2O emissions, fertilizer production and transport, power, other sources, CH_4 uptake and SOC sequestration, respectively. In contrast, the GHGI of the optimum (N_{opt} and SN_{opt}) N applications averaged 255 kg CO_2-eq Mg^{-1} grain, including contributions of 86, 183, 161, 64 and −236 kg CO_2-eq Mg^{-1} grain from N_2O emissions, N fertilizer production, power, other sources and SOC sequestration, respectively. The GHGI of conventional (N_{con} and SN_{con}) N application averaged 350 kg CO_2-eq Mg^{-1} grain, including contributions of 149, 378, 146, 58 and −378 kg CO_2-eq Mg^{-1} grain from N_2O emissions, N fer-
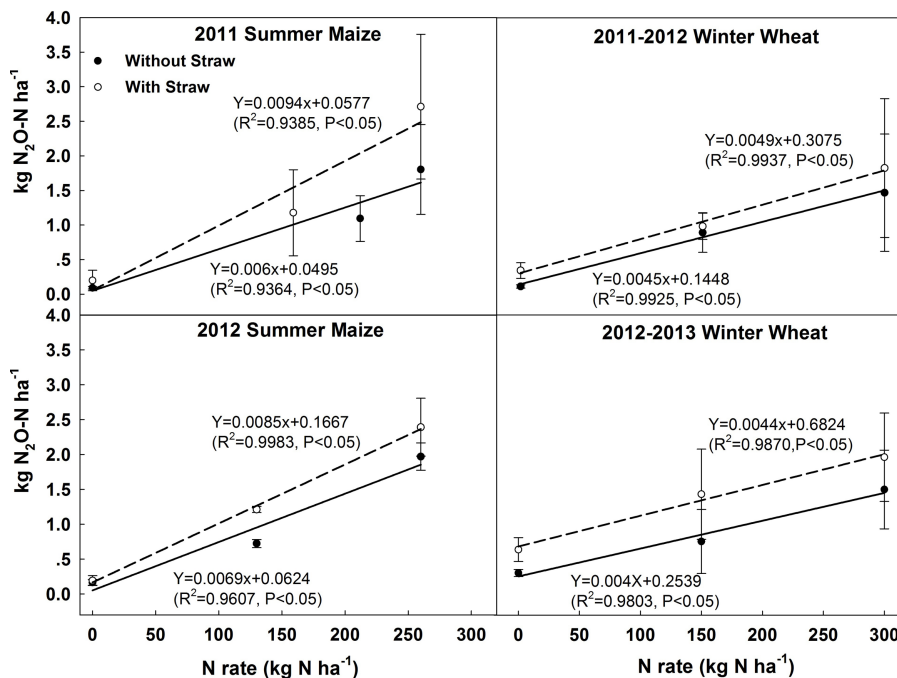
Fig. 4. Correlations between seasonal cumulative N_2O emissions and fertilizer N application rates from 2011 to 2013. The dashed line and solid line were fitted by linear regression from the straw and without straw treatments, respectively.

tilizer production, power, other sources and SOC sequestration, respectively. Compared to conventional N application, the GHGI at the optimum N treatment decreased by 95 kg CO_2-eq Mg^{-1} grain, with 62, 193 and -142 kg CO_2-eq Mg^{-1} grain of this due to a decrease in N_2O emissions, N fertilizer production and transport, and SOC sequestration, and 18 kg CO_2-eq Mg^{-1} grain due to an increase from other sources. Compared to straw removal, although the GHGI with straw return was 28 kg CO_2-eq Mg^{-1} grain due to a increase in N_2O emissions, this was offset by 144 and 9 kg CO_2-eq Mg^{-1} grain due to SOC sequestration and other sources, and finally decreased by 125 kg CO_2-eq Mg^{-1} grain.

4 Discussion

4.1 Effects of N application and straw return on grain yields

The mean grain yields (dry matter) of winter wheat (5.0 Mg ha^{-1}) and summer maize (6.8 Mg ha^{-1}) from the N application treatments (N_{opt} and N_{con}) in this study (Table 3) were comparable to the normal average yield in conventional farming practice on the NCP (wheat 5.5 Mg ha^{-1}, maize 5.5–6.0 Mg ha^{-1}) as reported by Zhao et al. (2006), and lower than the potential productivity (wheat 6.9 Mg ha^{-1}, maize 8.3 Mg ha^{-1}) based on the results of experiments conducted in the region (Wang et al., 2010). This further supports the argument that about half of the conventional N application

rate could be used to achieve comparable crop yields because the conventional practice has involved substantial over-use of chemical N fertilizers over the last decade, leading to pollution of surface waters and groundwater and high emissions of reactive N to the atmosphere (Ju et al., 2009; Guo et al., 2010; Liu et al., 2013). There is considerable scope for saving N fertilizer to restore the environment and maintain relatively high crop productivity.

It was locally common practice to remove straw and burn it as a household fuel about 20 years ago, but nowadays most straw is returned to the field because of a switch of household fuel to coal or natural gas (Edwards et al., 2004). These changes provide good opportunities to enhance soil fertility, store more carbon in the soil and boost crop yields (Huang and Sun, 2006). As shown in our study, straw return slightly increased winter wheat and summer maize yields (Table 3) and might increase the yields significantly as the experiment continues over the longer term (Malhi et al., 2011).

4.2 Impacts of N application and straw return on SOC sequestration and N_2O emissions

SOC density change represents the net CO_2 exchange between the atmosphere and soil (Mosier et al., 2006; Shang et al., 2011). It has been reported that chemical N fertilizer can increase the SOC content, especially with incorporation of straw (Huang and Sun, 2006), but the magnitude of the increase is subject to considerable temporal and spatial variation depending on initial SOC content, soil–climatic

conditions, management practices such as tillage, and cropping systems (Zhang et al., 2010). A local 25 yr old field experiment showed that the SOC content in the top 20 cm increased by 10–53 % compared with the control with N fertilizer application and maize straw return (Du et al., 2009). In our study the rate of increase of SOC density ranged from 0.04 to 1.44 Mg C ha^{-1} yr^{-1}, similar to previous reports from work in the uplands of northern China (0.07–1.461 Mg C ha^{-1} yr^{-1}) (Zhang et al., 2010). However, the change was very slow due to the decomposition of the straw coupled with high soil temperatures and moisture in summer on the NCP (Huang et al., 2013).

The processes, patterns and factors controlling N$_2$O emissions have been reported by several studies recently (Ju et al., 2011; Cui et al., 2012; Hu et al., 2013), i.e. N$_2$O emission peaks occurring mainly within one or two weeks of NH$_4^+$-based fertilizer application and irrigation, and the occurrence of emissions mainly during the summer maize season with combined high soil temperatures and moisture. Our results are in line with these earlier studies. N$_2$O emissions usually increase linearly or exponentially with increasing N application rate, and thus reduction of the N rate to an optimum level could substantially reduce N$_2$O emissions in cropping systems (Van Groenigen et al., 2010; Liu et al., 2012). Our former results using an automated system showed that total N$_2$O emissions decreased by 40 and 67 % in the winter wheat and summer maize seasons, respectively, when the conventional N management (300 kg N ha^{-1} per crop) changed to optimum N management (50–122 kg N ha^{-1} per crop) (Ju et al., 2011), which is similar to the 37–56 % reduction in the present study.

Straw return consistently increased N$_2$O emissions and showed positive interactions between N and straw, especially in the summer maize season (Fig. 4). This indicates that the N$_2$O emissions from the straw incorporation treatments were 4 times higher than the straw removal treatments (Hao et al., 2001). In addition, N$_2$O emissions increased by 58 % in the following summer maize after wheat straw return (Liu et al., 2011). This increase may have been due to accelerating microbial nitrification and denitrification processes with the coupling of mineral N, available carbon, and favourable temperatures and soil moisture (Huang et al., 2004).

4.3 Impacts of N application and straw return on NGWP and GHGI

Agricultural management practices that change one type of GWP source/sink may also impact other sources/sinks and therefore change the NGWP and GHGI (Mosier et al., 2006; Shang et al., 2011). In the present study a 56 % decrease in N fertilizer to the N$_{opt}$ treatment brought about a 47 % decrease in N$_2$O emissions, a 56 % decrease in N fertilizer manufacture and transport, a 43 % decrease in SOC sequestration, and finally a 34 % decrease in the net GWP relative to the N$_{con}$ treatment. However, despite the lower N fertilizer input, the grain yield declined by only 9 % (and not significantly) and the GHGI of the N$_{opt}$ treatment was 27 % lower than the N$_{con}$ treatment, indicating less CO$_2$-eq consumption per unit grain produced. Similarly, compared to the straw removal treatments, straw return generated a 28 % increase in N$_2$O emissions, 9 % increase in fuel consumption for straw returning, a 49 % increase in SOC sequestration, and finally 30 and 33 % decreases in NGWP and GHGI, respectively. Thus, this indicates that relatively high yields and lower carbon costs can be achieved simultaneously by optimizing N- and straw management.

The NGWP in our study (1346–4684 kg CO$_2$-eq ha^{-1}) was much lower than in rice–wheat rotations (6660–9710 kg CO$_2$-eq ha^{-1}) (Ma et al., 2013) and double-rice-cropping systems (13 407–26 066 kg CO$_2$-eq ha^{-1}) (Shang et al., 2011), in both of which CH$_4$ emission was the main contributor to the high GWP. However, CH$_4$ is a very small sink in our upland cropping system and CH$_4$ uptake makes little contribution when calculating the NGWP from all emissions and sinks. We therefore adopted the CH$_4$ uptake data from previous field experiments carried out on the same soil type, climatic zone and cropping system, and the annual and treatment variation in CH$_4$ uptake was very small (e.g. 0.74–1.16 kg CH$_4$-C ha^{-1} in 2009–2010 and 0.69–0.93 kg CH$_4$-C ha^{-1} in 2010–2011 across all treatments) (Gao, 2012; Hu et al., 2013). The effect of nitrogen and straw on cumulative CH$_4$ uptake in this region is very small (Liu et al., 2012) and the negative GWP from CH$_4$ uptake represented less than 1 % in all GWP calculations.

The GHGI values of the N application treatments were 252–393 kg CO$_2$-eq Mg^{-1} grain in this study, higher than the values from irrigated maize in central Nebraska, where the GHGI was 230 kg CO$_2$-eq Mg^{-1} grain (Grassini and Cassman, 2012) because of low emission factors for N fertilizer production (2.6 kg CO$_2$-eq kg^{-1} in the US vs. 8.3 kg CO$_2$-eq kg^{-1} in China) and electricity generation (0.6 kg CO$_2$-eq (kW h)$^{-1}$ in the US vs. 1.3 kg CO$_2$-eq (kW h)$^{-1}$ in China) (Grassini and Cassman, 2012; Zhang et al., 2013). The higher emission factor was due 70 and 86 % to Chinese primary energy consumption and the energy consumed in N fertilizer production being dependent on coal (Crompton and Wu, 2005; Zhang et al., 2013), which has a greater GWP (methane and carbon dioxide emission from mining and combustion of coal) and lower energy efficiency than other sources of energy such as natural gas and nuclear power (Zhang et al., 2013). In the present study the GHGI from the N fertilizer and electricity production accounted for 37–50 and 19–34 % of the total positive GHGI, respectively. However, if we adopt the lower emission factor (4.7 kg CO$_2$-eq kg^{-1}) for the N fertilizer industry in China by the best available technologies and a lower emission factor (0.24 kg CO$_2$-eq (kW h)$^{-1}$) for producing electricity by hydro power (Zhang et al., 2013), the GHGI for the N application treatments will be reduced to 35–101 kg CO$_2$-eq Mg^{-1} grain.

Our results show that 48–52 % of positive GWP from the agricultural inputs has been offset by SOC sequestration with a low initial SOC content ($7.7 \, g \, kg^{-1}$). However, this trend of increasing SOC content might slow down when it reaches a maximum soil C capacity, i.e. soil C saturation (West and Six, 2007). Moreover, different agricultural management practices that increase SOC will simultaneously change other types of greenhouse gas emissions (Robertson et al., 2000). Robertson et al. (2000) revealed that no-till management enhanced SOC accumulation but concomitantly stimulated N_2O emissions, which almost offset the negative GWP from SOC sequestration. Fertilizers and wheat residues applied to the soil will provide additional SOC in Ohio Crosby soil, but its greenhouse mitigating effect would be offset not only by increasing N_2O emissions but also by SOC sequestration rates decreasing with time, and as a result the GWP-lowering effect of the fertilized and unfertilized treatments will vanish after 7 and 12 years, respectively (Jacinthe and Lal, 2003). Nevertheless, this overestimation of SOC sequestration is unlikely to change our conclusion that optimum N fertilization and straw return can both maintain relatively high target yields and also reduce environmental costs in our cropping system.

In our study the main emission sources are power consumption for irrigation, N production and N_2O emissions, with the main emission sink being SOC sequestration. To further reduce the GWP of the winter wheat–summer maize cropping system in future, we firstly can change the current conventional cropping system (winter wheat–summer maize with two harvests in one year) to an alternative system (winter wheat/summer maize–spring maize with three harvests in two years or monoculture spring maize with one harvest each year) and reduce the power consumption for irrigating winter wheat as described by Meng et al. (2012). Secondly, we can reduce the GHG emissions generated from N fertilizer production by optimizing the N application rate (Ju et al., 2011; Liu et al., 2012) and improving the technologies of fertilizer N manufacturing technologies (Zhang et al., 2013). Thirdly, N_2O emissions can be reduced by using nitrification inhibitors (Ding et al., 2011) or polymer-coated controlled-release fertilizers (Hu et al., 2013). Finally, although in this study the highest SOC had increased to $10.8 \, g \, kg^{-1}$ after 6 years, there was still potential to increase SOC further by manure application and reduced tillage (Smith et al., 2007; Snyder et al., 2009).

5 Conclusions

The conventional N application rate could be reduced by roughly half to the optimum level using the improved Nmin method and still maintain relatively high target yields and consequently significantly reduce N_2O emissions. Straw return had a slight yield benefit and could increase annual N_2O emissions but led to a significant increase in SOC. Ra-

tional long-term N and straw return management can increase SOC sequestration, which can offset the CO_2-eq from GHG emissions and agricultural inputs and consequently reduce NGWP and GHGI compared with conventional farming practices in this double-cropping system. The main emission sources are the power consumption for irrigation, fertilizer N production and N_2O emissions, with SOC sequestration providing the main emission sink. Therefore, the NGWP and GHGI of this cropping system can be further decreased by water saving in the winter wheat season, improving the technologies of fertilizer N manufacture and reducing N_2O emissions by using slow-release or controlled-release fertilizers.

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